§7. New Thermodynamical Force in Plasma Phase Space that Controls Turbulence and Turbulent Transport

Itoh, S.-I. (Kyushu Univ.), Itoh, K.

Physics of turbulence and turbulent transport has been developed on the central dogma that spatial gradients constitute the controlling parameters, such as Reynolds number and Rayleigh number. Recent experiments with the nonequilibrium plasmas in magnetic confinement devices, however, have shown that the turbulence and transport change much faster than global parameters, after an abrupt change of heating power [1]. Here we propose a theory of turbulence in inhomogeneous magnetized plasmas, showing that the heating power directly influences the turbulence [2]. New mechanism, that an external source couples with plasma fluctuations in phase space so as to affect turbulence, is investigated. It is shown theoretically that

1. The plasma heating power directly influences the turbulence, without waiting the change of plasma parameters and their spatial gradients. This effect (i.e., immediate impact) is more effective for fluctuations with long-wave lengths.
2. New control parameter, $[\partial P_{heat}/\partial p]a^2/\chi_N$, is analogous to the Reynolds number which is the 'inhomogeneity-driven rate of change' normalized to diffusion rate, but is novel in the way that the thermodynamical force is the rate of change in velocity space (not in real space). (Here, P_{heat} is the heating power density, p is the plasma pressure, a is the plasma radius (characteristic scale length of spatial gradient), and χ_N is the turbulent thermal diffusivity.
3. Accordingly, the turbulent transport increases when the heating power is switched on, if $\partial P_{heat}/\partial p > 0$.
4. The condition under which this new effect can be observed is also evaluated.

The essence of the new mechanism that affects turbulence and turbulent transport in plasmas is illustrated. The distribution function is separated into the mean and perturbation as $f = f_0 + \tilde{f}$. The source in the phase space S naturally contains the component, which is coherent to the fluctuation of interest,

$$S[f; \boldsymbol{v}, \boldsymbol{x}, t] = S_0 + \tilde{f}\partial S[f_0; \boldsymbol{v}, \boldsymbol{x}, t]/\partial f_0 .$$

This new term represents the *change rate* of distribution function by heating, and it directly couples with and affects the fluctuations. This term jumps at the on/off of heating, so that the on/off of heating can immediately influence the fluctuation dynamics, without waiting the slower change of the mean f_0.

In order to examine this new effect, we employ fluid-like equations in describing the turbulence in magnetically-confined inhomogeneous plasmas [3]. We simply choose the case that the external heating source, $P_{heat}(x,t)$, is sensitive to pressure perturbation p,

$$P_{heat}(x,t) = P_{heat}(x,t) + \tilde{p}\partial P_{heat}/\partial p + \cdots,$$

where $\tilde{p}\partial P_{heat}/\partial p$ is the modulation of heating power which is induced by the presence of the fluctuations.
By use of a method of the dressed test mode, the dynamical equation of fluctuations in magnetized turbulent plasmas has been derived, to which the effect of heating is introduced, as,

$$\{\partial_T + \boldsymbol{L}\}\tilde{\boldsymbol{f}} = \left(0, 0, (\partial P_{heat}/\partial p)\tilde{p}\right)^T$$

where $\tilde{\boldsymbol{f}} = (\phi, J, p)^T$ denotes the fluctuating fields, $\boldsymbol{L}$ is the renormalized operator, which includes the linear instability mechanisms and the decorrelation by ambient turbulence. The long-range fluctuations, the radial correlation length of which is of the order of plasma size, are nonlinearly driven fluctuations can have substantial influence on turbulent transport [4]. By solving the stochastic equation, the mean amplitude of the linearly-stable global mode in the turbulent plasma is given as

$$\langle \varphi_1 \varphi_1 \rangle = \frac{1}{1 - F\chi_N^{-1}k_\perp^{-2}} \langle \varphi_1 \varphi_1 \rangle_0$$

where $F \equiv \partial P_{heat}/\partial p$ and $\langle \varphi_1 \varphi_1 \rangle_0$ is the intensity in the absence of the effect of the heating.

From this result, we see that an enhancement of the long-range fluctuation is prominent if $F/\chi_N k_\perp^2 \to 1$. That is, rewriting the wavelength in terms of the global scale length, $k_\perp^{-1} \sim a$, the condition for the strong influence of the heating power on fluctuations is written as $a^2\chi_N^{-1}\partial P_{heat}/\partial p \to 1$. The new control parameter, $[\partial P_{heat}/\partial p]a^2/\chi_N$, is in one hand analogous to the Reynolds number which is the 'inhomogeneity-driven rate of change' normalized to decorrelation rate by diffusion. This is novel because the thermodynamical force $\partial P_{heat}/\partial p$ is the rate of change not in real space but in velocity space. The value $[\partial P_{heat}/\partial p]a^2/\chi_N$ can be $O(1)$ in the experimental condition of ref.1, if one uses an estimate $\partial P_{heat}/\partial p \simeq P_{heat}/p$.

[1] Inagaki, S., et al., submitted to *Phys. Rev. Lett.* (2012).
[2] Itoh S. -I. & Itoh, K., Sci. Rep. **2** (2012) 860.
[3] Itoh, K., et al.: *Plasma Phys. Contr. Fusion* **42**, 855-861 (2000).
[4] Itoh S. -I. & Itoh, K., *Plasma Phys. Control. Fusion* **43**, 1055-1102 (2001).